FWM Compensation in DPSK Transmission by Reducing Detectors with Digital Coherent Detection Using Backward Propagation

Jing Liang, *Student Member* and Katsushi Iwashita, *Member, IEEE*

***Abstract*—Four-wave mixing (FWM) impairments become severe increasingly, since optical amplifiers are required increasingly for long-transmission distance in wavelength-division multiplexing (WDM) transmission systems. With backward propagation method, the FWM impairments can be completely compensated theoretically using detectors whose number is the same as the number of new frequencies that new generated FWMs locate on. However, we consider the compensation possibility by detecting only signal channels in this paper. Our compensation possibilities for non-degenerate case of FWM of differential phase-shift keying (DPSK) transmission have been experimentally demonstrated in a three-channel WDM system through off-line digital signal processing by coherent detection. For FWM compensation, fixed phase relationship among local oscillators (LO) after coherent detection is realized by modulating a LO light using a phase modulator. The eye penalty with P_0=8dBm is improved by 3.6dB, 4.9dB, 3.2dB, respectively, for individual signal. The compensation results indicate that the input optical power tolerance is improved by more than 4dB. And the FWM degradation compensation is also considered by reducing numbers of the detectors.**

***Index Terms*—Backward Propagation, Coherent Detection, Four Wave Mixing (FWM), Wavelength- Division Multiplexing (WDM).**

I. Introduction

In nowadays optical networks, transmission capacity has been increasing due to wavelength-division multiplexing (WDM) system. WDM is a promising technology to accommodate the explosive growth of the Internet and telecommunication traffic in wide-area and local-area network. Numerous channels at different wavelengths can be multiplexed on the same fiber in order that broad available bandwidth can be utilized. Therefore, the development of WDM is required extensively to satisfy the high capacity applications of the network users. Under nowadays requirements on transmission system, long transmission distance and more repeaters are needed and amplifier is more and more utilized indispensably. With the level of launched optical power increases, fiber nonlinearity becomes prominent increasingly, which lead to interference, distortion, and excess attenuation of the transmitted signals and then induce system degradations.

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There are several nonlinear effects in WDM systems, such as stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS), self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). FWM impairments become more and more severe in dense WDM systems. The system performance will not be undermined by cumulative dispersion if the dispersion-shifted fiber (DSF) is employed instead of standard single mode fiber (SMF), since both low dispersion and low attenuation are obtained. However, FWM effect will be more likely appear because of the so-called phase-matching condition. A *N*-channel WDM system will produce a large number of FWM components as many as $N^2(N-1)/2$ [1]. During the FWM generation, the signal power will be transferred to the new FWM frequencies, and the decrease of original channels power makes it more difficult to detect the signals correctly after a long distance transmission. A more detrimental consequence is that some of the FWM components will coincide with the signal channels. For this case, the FWM will act as noise on signal channels and lead to even greater degradation on overall system performance. Much attention has been attracted based on FWM induced degradation, since FWM effect become the primary source of inter-channel crosstalk when signals are transmitted near zero dispersion wavelength. Optical coherent detection combining electrical post compensation using digital signal processing is studied extensively and considered as a promising technology, since it can compensate not only fiber nonlinearity but also chromatic dispersion (CD) and polarization-mode dispersion (PMD) with backward propagation [2]. Moreover, post compensation offers great flexibility to the transmission length and fiber characteristics, comparing with the methods of dispersion management [3], [4], un-equal channel spacing [5], [6] and pre-distortion [7]. We have already experimentally demonstrated the feasibility of FWM post-compensation with digital coherent detection method through backward propagation [8].

With backward propagation method, the FWM impairments can be completely compensated theoretically using detectors whose number is the same as the number of channels (frequencies) that FWM components locate on. However, we consider the compensation possibility by detecting only signals channels in this paper. We experimentally demonstrate a three-channel WDM system with differential phase-shift keying (DPSK) modulation to clarify the possibility of non- degenerate case of FWM compensation using backward propagation. Fixed phase relation among local oscillators (LO) after coherent detection is realized by modulating a LO light using a phase modulator to realize the compensation. By our compensation, the eye penalty with P_0=8dBm is improved by 3.6dB, 4.9dB, 3.2dB, respectively, for each signal. The input optical power tolerance is improved by more than 4dB. We also consider the compensation for individual signal. It is possible to compensate the FWM degradation by reducing numbers of the detectors. The improved eye penalty for target signal is approximately the same as that of overall compensation.

II. WDM System with FWM Compensation by Digital Coherent Detection Using Backward Propagation

A. WDM Transmission Systems with FWM Compensation

The configuration of fiber nonlinearity compensation with coherent detection for WDM transmission system is shown in Fig.1. The signal distortions induced by fiber nonlinearities such as FWM, XPM are affected by other channels in WDM transmission systems. Therefore, other channel information is needed for compensation. Especially, FWM impairments compensation requires not only the powers from newly generated channels but also the phase information of each channel. If different LOs are utilized, there is no relationship between each LO, and the detected electrical signals on different channels have different phases after coherent detection. They cannot be distinguished. Therefore, fixed phase relationship between different channels are required. For this reason, phase locked LOs are employed for fiber nonlinearity compensation in WDM transmission systems. Moreover, the information from out of the signal channels is required for FWM compensation, since FWM-induced new channels also include the information of distortion. In Fig.1, the extra channels indicated with red are utilized for only FWM components adjacent to the WDM channels.

The FWM impairments can be completely compensated theoretically using detectors whose number is the same as the number of frequencies that FWM locate on. However, we consider the compensation possibility by detecting only signals channels in the following part.

Polarization dispersion compensation should also be included when the transmission is long and with high speed, whereas the polarization dispersion compensation is not shown in this figure. The compensated signals are combined after compensating the polarization dispersion of the detected signals. Fiber nonlinearity, chromatic dispersion and fiber loss are compensated simultaneously.

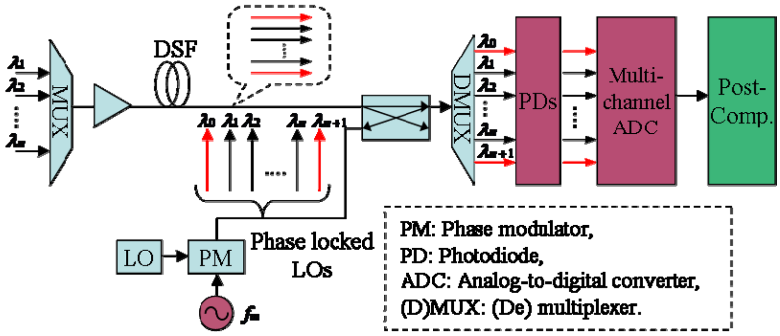


Figure 1 Configuration of fiber nonlinearity compensation with digital coherent detection in WDM system

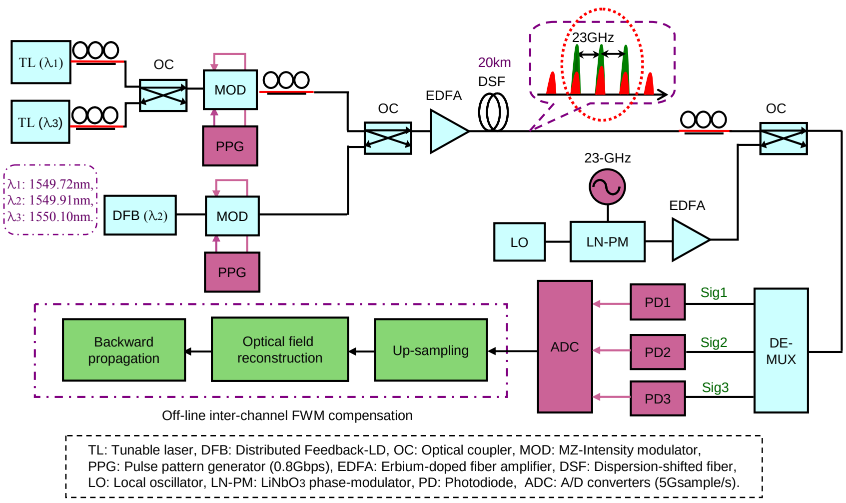


Figure 2 Experimental setup for compensating non-degenerate case of FWM

B. Coherent Detection

Coherent detection is utilized rather than direct detection since phase coherence of optical carrier plays a significant role in optical communication systems. If the optical signal is described as:

$$E_S = A_S \exp\left[-i\left(\omega_0 t + \phi_S\right)\right] \quad (1)$$

where A_S is the amplitude, ω_0 is the carrier frequency, and ϕ_S is the phase. The optical field of LO is given as:

$$E_{LO} = A_{LO} \exp\left[-i\left(\omega_{LO} t + \phi_{LO}\right)\right] \quad (2)$$

where A_{LO}, ω_{LO}, and ϕ_{LO} is the amplitude, frequency, and the phase of the LO, respectively. Then the optical power incident at the photo-detector is given by:

$$P(t) = P_S + P_{LO} + 2\sqrt{P_S P_{LO}} \cos\left(\omega_{IF} t + \phi_S - \phi_{LO}\right) \quad (3)$$

where $P_S = KA_S^2$, $P_{LO} = KA_{LO}^2$, $\omega_{IF} = \omega_0 - \omega_{LO}$, and K represents a constant. Therefore, the photocurrent is described as:

$$I(t) = R\left(P_S + P_{LO}\right) + 2R\sqrt{P_S P_{LO}} \cos\left(\omega_{IF} t + \phi_S - \phi_{LO}\right) \quad (4)$$

where R is the detector responsivity.

For heterodyne detection, since $P_{\mathrm{LO}} \gg P_{\mathrm{S}}$ in practice and the direct-current term is nearly constant, the alternating-current is substituted for Eq. (4) and written as:

$$I(t) = 2R\sqrt{P_S P_{LO}} \cos\left(\omega_{IF} t + \phi_S - \phi_{LO}\right) \quad (5)$$

From Eq. (1), the signal frequency and phase information will be lost after the square-law detection of direct detection, so the FWM impairments compensation cannot be substituted. However, coherent detection conserves the optical field in the detected electrical signal. Amplitude, phase and frequency can be kept well after the detection. For the case of our FWM compensation with backward propagation, the phase information can be utilized correctly.

C. Compensation Principle of Off-line Digital Signal Processing through Backward Propagation

For the off-line digital signal processing through backward propagation of the total-field comprising the compensation for fiber loss, CD and fiber nonlinearity, it is easier to understand the split-step Fourier method when we reform Nonlinear Schrodinger Equation (NLSE) [9] as:

$$\frac{\partial E}{\partial z} = \left(i\gamma' \left|E\right|^2 - \frac{i\beta_2'}{2}\frac{\partial^2}{\partial t^2} + \frac{\beta_3'}{6}\frac{\partial^3}{\partial t^3} - \frac{\alpha'}{2} \right) E \quad (6)$$

where $E=E\ (t, z)$ is the slowly varying complex amplitude of the optical field envelope at the time of t and length of z along the fiber; γ', β_2', β_3', α' are fiber nonlinear parameter, group velocity dispersion, the 3rd-order dispersion parameter and fiber-loss coefficient, respectively. Here, β_2', β_3', γ' can be expressed as:

$$\beta_2' = \frac{D_c \lambda^2}{2\pi c} \quad (7)$$

$$\beta_3' = -\frac{S}{\left(2\pi c/\lambda^2\right)^2} \quad (8)$$

$$\gamma' = -\frac{2\pi n_2}{\lambda A_{eff}} \quad (9)$$

where D_c is the fiber chromatic dispersion, λ is light wavelength, c is light velocity in vacuum, S is the dispersion slope, n_2 is the nonlinear-index, and A_{eff} denotes the effective core area of the fiber. As these three parameters are chosen precisely opposite-sign value with respect to the transmission fiber and the optical fiber is divided into several steps, the fiber nonlinearity, fiber CD and fiber loss can be compensated at each step through the backward propagation.

III. Experimental Setup

Figure 2 shows the experimental setup for non-degenerate case of FWM compensation with coherent detection. Two tunable lasers (TL) and one distributed feedback (DFB) laser with 23-GHz channel spacing are employed as WDM signal sources whose wavelengths are around 1550nm. They are DPSK modulated using individual Mach-Zehnder intensity modulator driven at a bit rate of 0.8Gbps by individual pulse pattern generator (PPG) with the pseudo-random bit sequence of 2^{12}-1 length. DPSK signals are utilized since DPSK is more resilient to some nonlinear effects, especially SBS. These three modulated signals are combined by a 3-dB optical coupler (OC), amplified by an Erbium-doped fiber amplifier (EDFA), and subsequently fed to a 20-km DSF whose zero-dispersion wavelength is around 1549nm. The optical spectra that before transmission and after transmission with the fiber input power P_0=8dBm/ch are shown in Fig. 3. The signal-to-FWM crosstalk ratio is nearly 10dB. Polarization controller (PC) is inserted appropriately that both channels are co-polarized. As shown in Fig.2, some of the generated new FWM components fall in the signal channels. Here, we consider the situation that only the transmitted signals are detected by each individual heterodyne detection receivers. Coherent detection conserves the optical field in the detected electrical signal then the signal can be compensated. For heterodyne detection, the phase relationship amongst different channels depends on the phase of LOs. The transmitted signals are detected with LOs which are modulated by a $LiNbO_3$ phase-modulator (LN-PM). Therefore, the phase relationship of the intermediate frequency (IF) signals can be kept fixed when they are detected by heterodyne detection with individual receiver. The center wavelength of LO is set near f_2 and the phase of the three detected signal channels f_1, f_2, f_3 are -π, 0, 0, respectively. The IF is about 1.6-GHz for heterodyne detection. The phase relationship between LOs and signals is shown in Fig.4. -π is adjusted to 0 while the compensation is carried on.

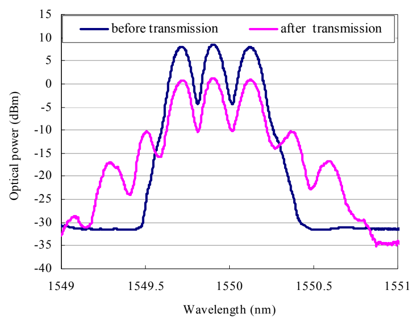


Figure 3 Optical spectra of transmitted signals (P_0=8dBm/ch)

The modulation index is adjusted to about 1.75, so as to realize the same sideband power as much as possible. The modulating frequency f_m is set as 23-GHz. The modulated LOs are amplified and coupled with the multiplexed signals by a 3-dB coupler. These coupled signals are demultiplexed by the optical demultiplexer. The optical spectra of individual signal after demultiplexer are illustrated in Fig.5. The received signals are sampled by three analog-to-digital converters (ADC) at a rate of 5Gsample/s.

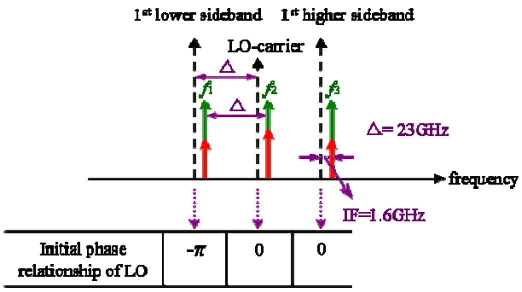


Figure 4 Phase relationship between LOs and signals

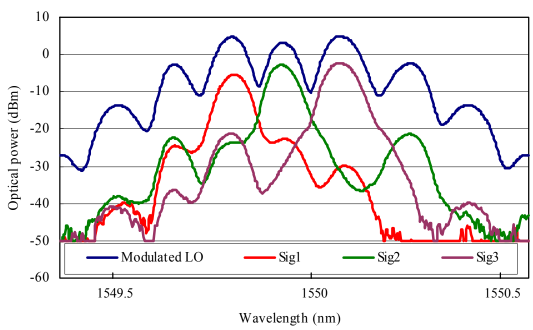
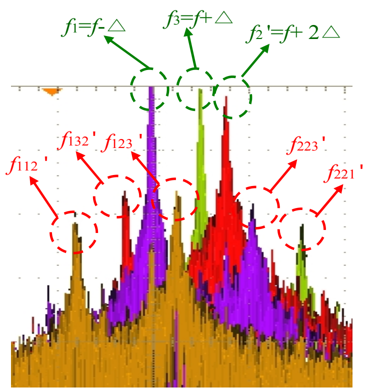


Figure 5 Optical spectrum of modulated LOs and individual signal

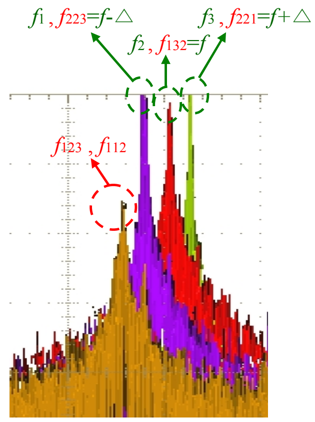
IV. RESULTS AND DISCUSSIONS

The converted signals are processed by an off-line digital signal processing. Each of the DPSK signals are first filtered by Hilbert filters to eliminate half of the signals which are in higher-frequency and up-sampled to a total bandwidth of 4×46-GHz. The up-sampled signals are combined with the channel spacing of 23-GHz for optical field reconstruction. The phase differences between the LO sidebands are considered when the received signals are combined. The individual optical powers are compensated to the fiber output powers which are measured before combining LOs. The combined signals are post-compensated through backward propagation which consists of nonlinear phase compensation, CD compensation and fiber loss compensation. The performance of FWM impairments compensation is evaluated by the eye penalty. Differential demodulation with one bit delay is carried on after the up-sampling. Then the demodulated signals are filtered by low-pass filters. The eye-diagrams are obtained by superposing all of the bits using the software that we made.

The center channel is the most severely degraded due to the frequency mixing from non-degenerate case of FWM. Figure 6 gives the electrical spectra of the IF signals which are measured by multi-channel oscilloscope. The purple, red, green spectra denote the three detected signal channels, respectively. The spectrum denoted as brown color is detected by another PD so as to view the frequency relation between FWM components. In order to observe the FWM components clearly, the frequency of center-channel signal (red signal) is adjusted to f+2Δ in the electrical domain as shown in Fig.6 (a). By frequency adjustment of the red signal f_2', the FWM components f_{223}', f_{132}', f_{221}' locate at f+3Δ, f-2Δ, f+5Δ, respectively. The signals and induced FWMs power influenced by polarization can be observed clearly and controlled easily. The components f_{223}', f_{132}', f_{221}' will fall in f_1, f_2, f_3 respectively when the red signal is adjusted to the center frequency f, while the components of f_{123} and f_{112} coincide with each other as shown in Fig.6 (b).



(a) spectrum for observing FWM components



(b) spectrum after frequency adjustment

Figure 6 Electrical spectrum of IF signals on ADC

The parameters for the compensation are chosen as follows: DSF fiber loss α, dispersion D_c, dispersion slope S and fiber nonlinear coefficient γ at 1550nm are 0.22dB/km, 0.07ps/km/nm, 0.07ps/km/nm^2, 3.04/W/km, respectively. The fiber is divided into 15 sections for this compensation. The eye openings are given in Fig. 7. Figure 7 a1-1), a2-1), a3-1) give the eye diagrams for three-DPSK-modulated signals, respectively, by 20-km transmission before compensation with P_0=4dBm/ch, while Fig. 7 a1-2), a2-2), a3-2) plot the eye diagrams after compensation, respectively, for this non-degenerate case of FWM. The eye penalty of each signal is improved by 1.1dB, 1.7dB, 1.9dB after compensation. Figure 7 b1-1), b2-1), b3-1) and b1-2), b2-2), b3-2) show the eye diagrams of individual signals w/o and w/ compensation of P_0=8dBm/ch, respectively, and each eye penalty is improved by 3.6dB, 4.9dB, 3.2dB, respectively. The graph of eye penalty improvement for each signal is shown in Fig. 8. It is clear that the eye penalty of each signal after compensation with P_0=8dBm is lower than that of before compensation with P_0=4dBm. These compensation results indicate that the input optical power tolerance is improved by more than 4dB.

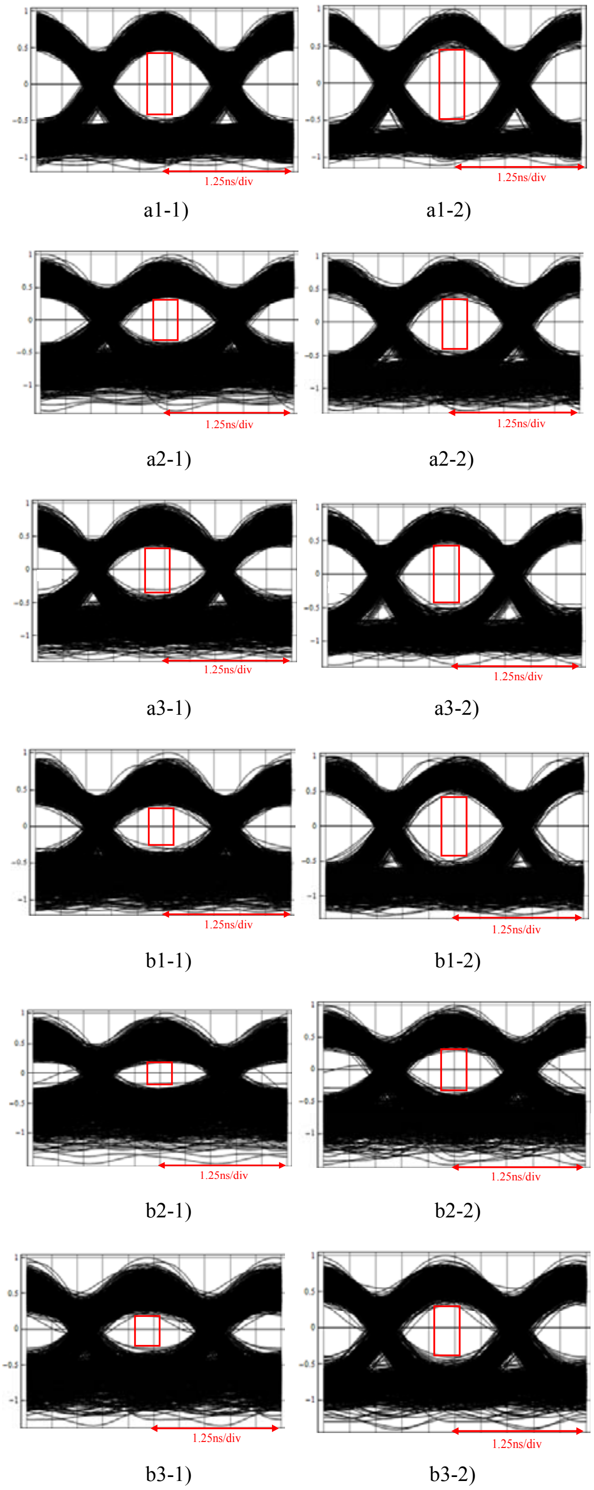


Figure 7 Eye diagrams of individual signal for a1-1), a2-1), a3-1) 20-km transmission w/o comp. with P_0=4dBm/ch; a1-2), a2-2), a3-2) 20-km transmission w/ comp. with P_0=4dBm/ch; b1-1), b2-1), b3-1) 20-km transmission w/o comp. with P_0=8dBm/ch; b1-2), b2-2), b3-2) 20-km transmission w/ comp. with P_0=8dBm/ch.

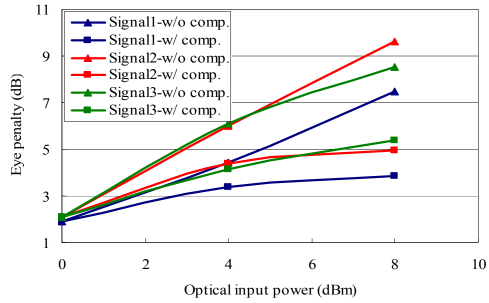
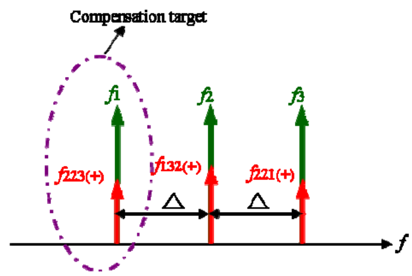
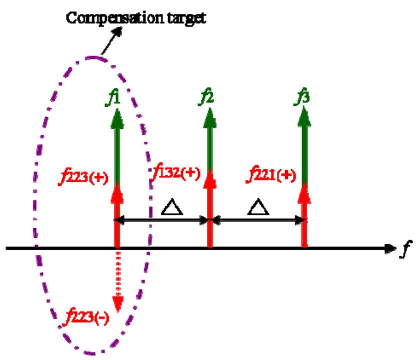


Figure 8 Eye penalty improvement for each signal

The transmitted signals can be compensated completely by increasing detectors' number up until the same as the number of frequencies that new generated FWM components locate on. However, here we consider the compensation by reducing detectors for individual signal. Take signal1 for example. Due to the frequency relationship, the FWM degradation on f_1 (signal1) is induced by the frequency mixing of signals located on f_2 and f_3 which is shown in Fig. 9. Here the symbol △ indicates the channel spacing. "+" represents the FWM appear in fiber propagation, and by compensation the new FWM marked by symbol "-" is generated with the opposite phase, so the FWM on f_1 can be canceled. Therefore, it is feasible for compensating f_1 using only f_2 and f_3 to the same degree as overall compensation using three detectors that is stated above. When signal1 is combined to these two IF signals processed by the backward propagation, it can be compensated to some extent.



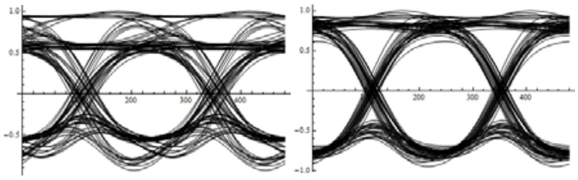
(a)



(b)

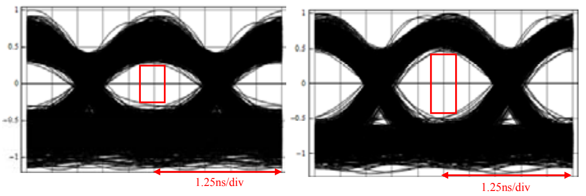
Figure 9 Principle of compensation for individual signal (△ here stands for the same channel spacing): (a) after transmission; (b) after compensation using only two signals.

The eye diagrams before and after compensation (for the bit length of 100) by simulation are shown in Fig. 10(a) and 10(b), respectively. Figure 11 gives the individual eye opening of f_1 and f_3 before and after compensation by using only two detectors with P_0=8dBm/ch. Compensating by only f_2 and f_3, the improved eye penalty of f_1 shown in Fig.11 a2) is almost the same as that of overall compensation in Fig.7 b1-2). In a similar way, the eye opening of f_3 in Fig.11 b2) is also the same as that of Fig.7 b3-2) by using only f_1 and f_2. The center channel cannot be compensated by only two detectors since the FWM components fall on it are the non-degenerate case.

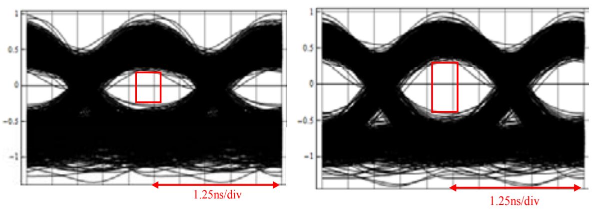


(a) (b)

Figure 10 Eye opening of signal1 by simulation for reducing detectors: (a) w/o compensation (b) w/ compensation



a1) a2)



b1) b2)

Figure 11 Eye opening of individual signal with P_0=8dBm/ch: a1) signal1 w/o compensation; a2) signal1 w/ compensation using only signal2 and signal3; b1) signal3 w/o compensation; b2) signal3 w/ compensation using only signal1 and signal2.

In order to study the influence factors of compensation result, we did the simulation based on three channel WDM system. It is highly probable that these compensation results can be improved if higher IF frequency is employed. However, the IF in experiment is limited by the sampling rate of multi-channel ADC. The insufficient power difference between LOs and transmitted signals also contribute to the undercompensation. Compensation performance can be improved if sufficient LO powers are realized.

V. Conclusions

The compensation possibilities in a three-channel WDM system through off-line digital signal processing by coherent detection have been experimentally demonstrated for non-degenerate case of FWM of DPSK transmission. The transmitted signals are detected with LOs which are modulated by a LN-PM in order that the phase relation between all of the phase-modulated LOs can be kept constant when the IF signals are received by each individual channel. The eye penalty with P_0=8dBm is improved by 3.6dB, 4.9dB, 3.2dB, respectively, for each individual signal. FWM degradation compensation is also considered by reducing numbers of the detectors.

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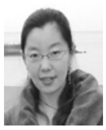

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